Search for New Physics Phenomena in Fermion-Pair Production at LEP

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The L3 Collaboration

Abstract

The measurements of hadron and lepton–pair production cross sections and lepton–pair forward–backward asymmetries performed with the L3 detector at centre–of–mass energies between 130 GeV and 172 GeV are used to search for new physics phenomena. New physics effects involving four fermion vertices – contact interactions – are looked for in all channels. For hadron production the exchange of virtual leptoquarks and scalar quarks is studied. No evidence for deviations from the Standard Model expectations is found. Lower limits on the scale Λ of contact interactions in the range 1.2 – 7.1 TeV are obtained at the 95% confidence level for various models. Upper limits on the coupling strengths of leptoquarks and scalar quarks are derived.

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Introduction

The successful running of LEP in 1995 and 1996 at centre–of–mass energies well above the Z resonance allows to search for new physics beyond the Standard Model [1]. Any significant deviation from the Standard Model predictions in the electron-positron annihilation into fermion-pairs would herald the presence of new phenomena. Four-fermion contact interactions offer a general framework for describing interactions beyond the Standard Model. They are characterised by a coupling strength, g, and by an energy scale, Λ, which can be viewed as the typical mass of new heavy particles being exchanged. For instance, if fermions are composite, such effects can occur. At energies much lower than Λ, the exchange of virtual new particles is described by an effective Lagrangian [2]:

$$\mathcal{L} = \frac{1}{1+\delta_{\mathrm{e}f}} \sum_{i,j=\mathrm{L,R}} \eta_{ij} \frac{g^2}{\Lambda_{ij}^2} (\bar{\mathrm{e}}_i \gamma^\mu \mathrm{e}_i)(\bar{f}_j \gamma^\mu f_j), \tag{1}$$

where e_i and f_j denote the left– and right–handed initial–state electron and final–state fermion fields. The Kronecker symbol, $\delta_{\mathrm{e}f}$, is zero except for the $\mathrm{e}^+\mathrm{e}^-$ final state where it is one. The parameters η_{ij} define the contact interaction model by choosing the helicity amplitudes which contribute to the reaction $\mathrm{e}^+\mathrm{e}^- \rightarrow f\bar{f}$. The value of g/Λ determines the size of the expected effects. In a general search for contact terms the energy scale Λ is chosen by convention such that $g^2/4\pi = 1$ and $|\eta_{ij}| = 1$ or $|\eta_{ij}| = 0$ is satisfied.

For hadronic final states two specific scenarios are investigated where t– or u–channel exchange of new particles coupling to quark–lepton pairs contribute. In the first scenario the exchange of leptoquarks [3, 4] is studied. In the second scenario the exchange of supersymmetric scalar quarks violating R–parity [5] is investigated.

In this paper, our measurements of hadron and lepton–pair cross sections and lepton–pair forward–backward asymmetries are used to search for the existence of contact interactions. The effects of virtual exchange of leptoquarks and scalar quarks are investigated using our hadron cross section measurements only. In a previous publication we have used our data to search for R–parity breaking scalar neutrino exchange [6]. Limits on contact interactions and on leptoquark and scalar quark couplings have been presented by the OPAL collaboration [7] at LEP and by the CDF and DØ collaborations at the Tevatron [8].

Measurements of Fermion–Pair Production

Measurements of cross sections and forward–backward asymmetries for the reactions $\mathrm{e}^+\mathrm{e}^- \rightarrow f\bar{f}$ have been performed by the L3 experiment at centre–of–mass energies, $\sqrt{s}$, of 130.3, 136.3 and 140.2 GeV [9], and at $\sqrt{s}$ = 161.3, 170.3 and 172.3 GeV [10]. The L3 detector and its performance are described in Reference [11].

For the $\mathrm{e}^+\mathrm{e}^-$ final states both leptons have to be in the polar angular range $44° < \theta < 136°$, where θ is the angle between the incoming electron and the outgoing lepton. Muon– and tau–pair candidates are selected with both leptons in the fiducial volume given by $|\cos\theta| < 0.9$. Hadron events are selected in the full solid angle.

In total 4305 hadron events and 1269 lepton–pair events are selected. These correspond to an integrated luminosity of 26.2 pb^{-1}. Due to the large Z exchange cross section the sensitivity to new physics is suppressed for centre–of–mass energies in the vicinity of the Z resonance. Therefore, a minimum effective centre–of–mass energy, $\sqrt{s'_{\mathrm{min}}}$, is required to reject radiative returns to the Z. The remaining samples contain in total 1179 hadron and 869 lepton–pair events.

Virtual effects in $e^+e^- \to f\bar{f}$

Contact Interaction

For a general theory at an universal energy scale $\Lambda \gg \sqrt{s}$, new interactions are described by an effective contact interaction as shown in Figure 1a. The differential cross section including a four–fermion contact interaction as a function of the final–state fermion scattering angle θ is given by [12]:

$$
\begin{aligned}
\frac{1}{N_c}\frac{2s}{\pi\alpha^2}\frac{d\sigma}{d\cos\theta} &= \left[|A^{ef}_{LR}(t)|^2 + |A^{ef}_{RL}(t)|^2\right]\left(\frac{s}{t}\right)^2\delta_{ef} + \\
&\left[|A^{ef}_{LR}(s)|^2 + |A^{ef}_{RL}(s)|^2\right]\left(\frac{t}{s}\right)^2 + \left[|A^{ef}_{LL}(s)|^2 + |A^{ef}_{RR}(s)|^2\right]\left(\frac{u}{s}\right)^2,
\end{aligned}
\tag{2}
$$

with

$$
\delta_{ef} = \begin{cases} 1, & \text{for } f = e \\ 0, & \text{for } f \neq e. \end{cases}
$$

The Mandelstam variables are denoted s, t and u. The electromagnetic fine structure constant and the colour factor are given by α and N_c, respectively. The electroweak and the four–fermion contact interaction contribute to the helicity amplitudes:

$$
\begin{aligned}
A^{ef}_{ij}(y) &= Q_e Q_f + g^e_i g^f_j \chi(y) + \eta_{ij}\frac{y}{\alpha}\frac{1}{\Lambda^2}; & (i \neq j) \\
A^{ef}_{ij}(s) &= Q_e Q_f + g^e_i g^f_j\left[\chi(s) + \frac{s}{t}\chi(t)\delta_{ef}\right] + \frac{s}{t}\delta_{ef} + (1+\delta_{ef})\eta_{ij}\frac{s}{\alpha}\frac{1}{\Lambda^2}; & (i = j),
\end{aligned}
\tag{3}
$$

where Q is the electric charge, χ is the Z propagator and y denotes either s or t. The left– or right–handed coupling, g^f_i, are

$$
g^f_L = \frac{1}{\sin\theta_W\cos\theta_W}(I^f_3 - Q_f\sin^2\theta_W)\,, \tag{4}
$$

$$
g^f_R = \frac{1}{\sin\theta_W\cos\theta_W}(-Q_f\sin^2\theta_W), \tag{5}
$$

where θ_W is the weak mixing angle and I^f_3 is the third component of the weak isospin. The differential cross section in Equation 2 is rewritten in a general form as

$$
\frac{d\sigma}{d\cos\theta} = \frac{d\sigma^{SM}}{d\cos\theta} + c_2(s,\cos\theta)\frac{1}{\Lambda^2} + c_4(s,\cos\theta)\frac{1}{\Lambda^4}. \tag{6}
$$

The coefficients c_i represent the deviations from the Standard Model cross section, σ^{SM}, depending on the contact interaction model. The pure contact interaction amplitude and the interference between the Standard Model and the new physics are given by the terms including c_4 and c_2, respectively. The helicity combinations of the specific models considered are defined in Table 1.

Leptoquark Exchange

Leptoquarks couple to quark–lepton pairs from the same family, and preserve the baryon number B and the lepton number L. In $\mathrm{e^+e^-}$ collisions, leptoquarks of the first generation can be exchanged in the t– or u–channel leading to hadron final states as depicted in Figure 1b. For leptoquarks the notation used in Reference [13] is adopted where scalar leptoquarks, S, and vector leptoquarks, V, are classified as follows:

- Based on spin and weak isospin, I, the leptoquarks are divided into S_I and V_I, where an additional tilde indicates isomultiplets with different hypercharges.
- Leptoquark couplings are denoted g_L, g_R, with L,R refering to the chirality of the lepton. In the t– and u–channel leptoquarks can only be exchanged for special helicity combinations $\mathrm{e^+e^-_{\mathit{i}}} \rightarrow q_j\bar{q}$ with $i,j = \mathrm{L,R}$.
- Leptoquarks carry fermion numbers, $F = L + 3B$. In the u–channel exchange $F = 2$ while in the t–channel exchange $F = 0$.

The total cross section of quark–pair production in Born approximation, including the exchange of one leptoquark with either left or right coupling, is described by [4]

$$\sigma(\mathrm{e^+e^-} \rightarrow q\bar{q}) = \sigma^{\mathrm{SM}}_{q\bar{q}} + \frac{N_\mathrm{c}}{128\pi s}\sum_{i=1}^{4} k_i(g^2_{\mathrm{L,R}})C_i(\frac{m^2_{\mathrm{LQ}}}{s}). \tag{7}$$

The interference between γ/Z and the leptoquark is described by the coupling coefficients $k_{1,2}$ and the functions $C_{1,2}$ and the squared leptoquark amplitude is given by the coupling coefficients $k_{3,4}$ and the functions $C_{3,4}$.

In the limit of $m_\mathrm{LQ} \gg \sqrt{s}$ the particle propagator approach of Equation 7 reduces to the contact interaction approach of Equation 6. The individual masses and couplings of leptoquarks are then related to the contact interaction scale by

$$\frac{g^2_{\mathrm{L,R}}}{m^2_{\mathrm{LQ}}} \sim \frac{1}{\Lambda^2_{ij}}. \tag{8}$$

Exchange of R–Parity Breaking Scalar Quarks

Even in a minimal supersymmetric model the most general superpotential contains interactions violating R–parity in the trilinear couplings of superfields [14]. The only renormalisable gauge invariant operator that couples leptons, fermions and their scalar partners is given by [15]:

$$W_{\not{R}} = \lambda_{ijk}L^i_\mathrm{L}L^j_\mathrm{L}\overline{E}^k_\mathrm{R} + \lambda'_{ijk}L^i_\mathrm{L}Q^j_\mathrm{L}\overline{D}^k_\mathrm{R}, \tag{9}$$

where L_L stands for the left–handed doublets of leptons, Q_L for the left–handed quark doublets and E_R and D_R for the right–handed singlets of charged leptons and down–type quarks. The family indices are i, j and k. Limits on the couplings of scalar tau neutrinos to electrons, λ_{131}, and to muons, λ_{232}, are derived in Reference [6] from our measurements of lepton–pair cross sections and forward–backward asymmetries. Similar studies for hadronic final states give limits on the couplings of scalar quarks to electrons and quarks, λ'_{1jk}, $(j,k = 1,2,3)$. The two possible scenarios are shown in Figure 1c.

In the t–channel the relevant coupling is λ'_{1jk}, where $j = 1,2,3$ is the family index of the exchanged scalar left–handed up–type quark, and $k = 1,2,3$ is the family index of the final state down–type quark. In this case the scalar quarks couple to fermions like the $\tilde{S}_{1/2}$ leptoquark. In the u–channel the relevant coupling is λ'_{1jk}, where $j = 1, 2$ is the family index of the final state up–type quark and $k = 1, 2, 3$ is the family index of the exchanged scalar right–handed down–type quark. In this case the scalar quarks couple to fermions in the same way as S_0 leptoquarks with left-handed coupling $g_{\rm L}$. At LEP centre–of–mass energies the coupling λ'_{13k} contributes only to the t–channel exchange since it is not possible to produce $\rm t\bar{t}$ final states. The scalar quark–exchange contributions are calculated using Equation 7.

Analysis and Results

The contributions of contact interaction and leptoquarks as given in Equations 2 and 7 are included into the improved Born cross section calculated with the program ZFITTER [16] and are convoluted to account for QED radiative corrections:

$$\sigma_{\rm t,fb} = \int_{s'_{\rm min}}^{s} \sigma^0_{\rm t,fb}(s') R_{\rm t,fb}(s,s') ds' \,, \tag{10}$$

$$A_{\rm fb} = \frac{\sigma_{\rm fb}}{\sigma_{\rm t}}. \tag{11}$$

The total Born cross section, $\sigma^0_{\rm t}$, and the difference between forward and backward Born cross sections, $\sigma^0_{\rm fb}$, include electroweak and QCD corrections for the Standard Model part. Initial and final state QED corrections are taken into account in Equation 10 by the radiator functions $R_{\rm t}$ and $R_{\rm fb}$.

In order to determine the contributions of contact interactions or leptoquarks, the Standard Model parameters are fixed to $\alpha_{\rm s}(m_{\rm Z})$=0.118 [17], $\alpha(m_{\rm Z})$=1/128.894 [18], $m_{\rm Z} = 91.195$ GeV [19], $m_{\rm t} = 175.6$ GeV [20] and $m_{\rm H} = 300$ GeV. The results of our analysis are not sensitive to the uncertainties on these parameters. The contributions of new physics are determined performing a χ^2–fit to cross section and asymmetry measurements. Statistical and systematic errors of the measurements are incorporated as determined in References [9, 10]. No deviations from the Standard Model expectations are seen. In their absence one sided lower limits at the 95% confidence level are derived for Λ and for $g_{\rm L,R}/m_X$ (X = LQ, $\tilde{q}$).

In some cases the χ^2–curve has more than one minimum. This is due to the quadratic form of the differential cross section in $1/\Lambda^2$ as given in Equation 6. In these cases the minimum with the smallest Λ that satisfies $\chi^2(1/\Lambda) \geq \chi^2(1/\Lambda_{\rm min}) + 3.84$ is taken as a conservative lower limit.

Limits on the Scale Λ of Four–Fermion Contact Interactions

The different models considered are summarised in Table 1. Atomic physics parity violation experiments probe with high precision the couplings of electrons to quarks of the first family, and place severe constraints on the scale Λ of the order of 15 TeV [21]. The VV, AA, V0 and A0 models are parity conserving and hence are not constrained by these measurements.

The four–fermion contact interactions for the different types of final–state fermions are tested separately as well as for all flavours combined and lower limits on the scale Λ are derived. For hadron final states the following cases are analysed: the contact interaction affects only one flavour of up–type or down–type quarks, or all flavours at the same time. The results are given in Table 2 and depicted in Figure 2. The lepton–pair final states are analysed separately for the three lepton channels and for all leptons combined. The lower limits obtained for Λ are summarised in Table 3 and Figure 3. The limits Λ_+ (Λ_-) correspond to the upper (lower) sign of the parameters η_{ij} in Table 1, respectively.

Limits on Leptoquark Couplings

Assuming leptoquarks with a mass of a few hundred GeV, upper limits on their couplings to quark–lepton pairs, $g_{\mathrm{L,R}}$, are derived. The exchange of different types of leptoquarks is studied separately. The states S_0, $S_{1/2}$ and V_0, $V_{1/2}$ couple to both left- and right-handed quarks. Here, only one coupling, g_{L} or g_{R}, is assumed to be non–zero since low energy processes and rare decays of π and K largely constrain the product $g_{\mathrm{L}}\, g_{\mathrm{R}}$ [22, 23].

The allowed values for $g_{\mathrm{L,R}}$ are symmetrically distributed around zero. Our limits are presented in Figure 4 for scalar leptoquarks and in Figure 5 for vector leptoquarks. For a leptoquark with $m_{\mathrm{LQ}} = 200$ GeV upper limits on the absolute value of the couplings, g_{L} and g_{R} in the range $0.2 - 1.0$ at the 95% confidence level are obtained.

The exchange of leptoquarks with higher masses is described by the interference and squared contact terms of Equation 6. In this case the left– and right–handed couplings satisfy Equation 8 and our limits approach those on contact interactions derived in the previous section.

Determination of Limits on R–Parity Violating Scalar Quarks

Upper limits on $|\lambda'_{1jk}|$ ($j, k = 1, 2, 3$) are derived assuming one single Yukawa coupling to be much larger than the others which are neglected. A strong constraint on the coupling λ'_{111} is derived from the neutrinoless double beta decay [24].

Here, two cases are analysed:

$$\begin{aligned} m_{\tilde{u}} &\gg m_{\tilde{d}} \quad \text{with} \quad \tilde{u} = \tilde{\mathrm{u}}, \tilde{\mathrm{c}}, \tilde{\mathrm{t}} \quad \text{and} \quad \tilde{d} = \tilde{\mathrm{d}}, \tilde{\mathrm{s}}, \tilde{\mathrm{b}} \\ m_{\tilde{u}} &\ll m_{\tilde{d}} \end{aligned}$$

Only the exchange of the much lighter scalar quark type is important. Due to quark–universality all limits derived for the case $m_{\tilde{u}} \gg m_{\tilde{d}}$ are the same. Analogously, all limits coming from the hypothesis $m_{\tilde{u}} \ll m_{\tilde{d}}$ agree with each other.

The amplitudes of right–handed scalar down–type quarks interfere with the helicity amplitude, A_{LL}, of the Standard Model, while amplitudes of left–handed scalar up–type quarks interfere with A_{LR} which is suppressed at centre–of–mass energies well above the Z resonance. Therefore the R–parity breaking Yukawa couplings are mainly restricted by virtual exchange of scalar down–type quarks in the u–channel. These limits are identical to those on $|g_{\mathrm{L}}|$ for S_0 leptoquark exchange shown in Figure 4a. In case of t–channel exchange of scalar quarks the limits on $|\lambda'|$ agree with the result of the $\tilde{S}_{1/2}$ leptoquark exchange shown in Figure 4b. Assuming scalar up–type and down–type quark masses to be equal and both contributing to the hadronic cross section yields basically the same limits as for the case $m_{\tilde{u}} \gg m_{\tilde{d}}$. For scalar quark masses with $m_{\tilde{q}} = 200$ GeV limits at the 95% confidence level of 0.4 and 0.8 for the two cases are obtained.

Conclusions

Our fermion–pair cross section and forward–backward asymmetry measurements are used to search for effects of new physics in terms of four–fermion contact interactions. No hint of deviations from the Standard Model is found. Limits on the energy scale Λ in the range 1.2 – 7.1 TeV are obtained.

The effects of the exchange of leptoquarks or R–parity violating scalar quarks in the u– or t–channel of hadron production are studied. In both cases, upper limits on the coupling constants, $|g_{\mathrm{L}}|$ and $|g_{\mathrm{R}}|$, or $|\lambda'|$ between 0.2 and 1.0 for masses $m_X = 200$ GeV at the 95% confidence level are determined.

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Model	LL	RR	LR	RL	VV	AA	V0	A0	LL−RR
η_{LL}	±1	0	0	0	±1	±1	±1	0	±1
η_{RR}	0	±1	0	0	±1	±1	±1	0	∓1
η_{LR}	0	0	±1	0	±1	∓1	0	±1	0
η_{RL}	0	0	0	±1	±1	∓1	0	±1	0

Table 1: Models of contact interaction considered. The parameters η_{ij} $(i,j = \mathrm{L,R})$ define to which helicity amplitudes, A_{ij}, the contact interaction contributes. The models cover the interference of contact terms with single as well as with a combination of helicity amplitudes.

	$f\bar{f}$		$q\bar{q}$		$\mathrm{u\bar{u}}$		$\mathrm{d\bar{d}}$	
	Λ_-	Λ_+	Λ_-	Λ_+	Λ_-	Λ_+	Λ_-	Λ_+
LL	3.2	4.0	2.1	3.0	2.8	3.3	3.0	2.7
RR	3.2	3.9	2.7	2.3	2.4	1.2	1.4	2.0
LR	3.0	3.3	2.6	2.4	1.9	1.5	1.6	1.8
RL	3.5	3.8	3.2	2.0	1.7	1.7	2.0	1.4
VV	5.8	7.1	3.9	3.2	3.8	1.5	1.8	3.1
AA	4.2	5.1	2.9	4.3	3.5	1.7	1.7	3.5
V0	4.4	5.4	2.8	3.2	3.5	4.3	3.5	3.1
A0	4.5	5.2	3.7	2.4	2.2	1.8	2.2	1.8
LL−RR	2.5	3.6	2.5	3.6	2.3	1.7	1.6	2.5

Table 2: The one–sided 95% confidence level lower limits on the parameter Λ of contact interaction derived from fits. The limits Λ_+ (Λ_-) given in TeV correspond to the upper (lower) sign of the parameters η_{ij} in Table 1, respectively.

	$\ell^+\ell^-$		e^+e^-		$\mu^+\mu^-$		$\tau^+\tau^-$	
	Λ_-	Λ_+	Λ_-	Λ_+	Λ_-	Λ_+	Λ_-	Λ_+
LL	3.1	4.0	2.4	2.7	2.4	3.6	2.8	2.4
RR	3.0	3.9	2.4	2.7	2.2	3.5	2.6	2.3
LR	3.0	3.4	2.8	3.3	1.5	2.4	1.4	2.1
RL	3.0	3.4	2.8	3.3	1.5	2.4	1.4	2.1
VV	5.8	7.1	4.8	6.4	4.4	5.3	4.5	3.7
AA	4.1	4.9	1.9	3.3	3.3	4.9	3.9	2.9
V0	4.4	5.5	3.2	4.1	3.5	4.9	4.0	3.1
A0	4.3	4.8	3.9	4.8	1.6	3.1	1.5	2.8
LL−RR	2.1	2.3	1.9	1.9	2.1	2.4	1.7	1.8

Table 3: The one–sided 95% confidence level lower limits on the parameter Λ of contact interaction derived from fits. The limits Λ_+ (Λ_-) given in TeV correspond to the upper (lower) sign of the parameters η_{ij} in Table 1, respectively.

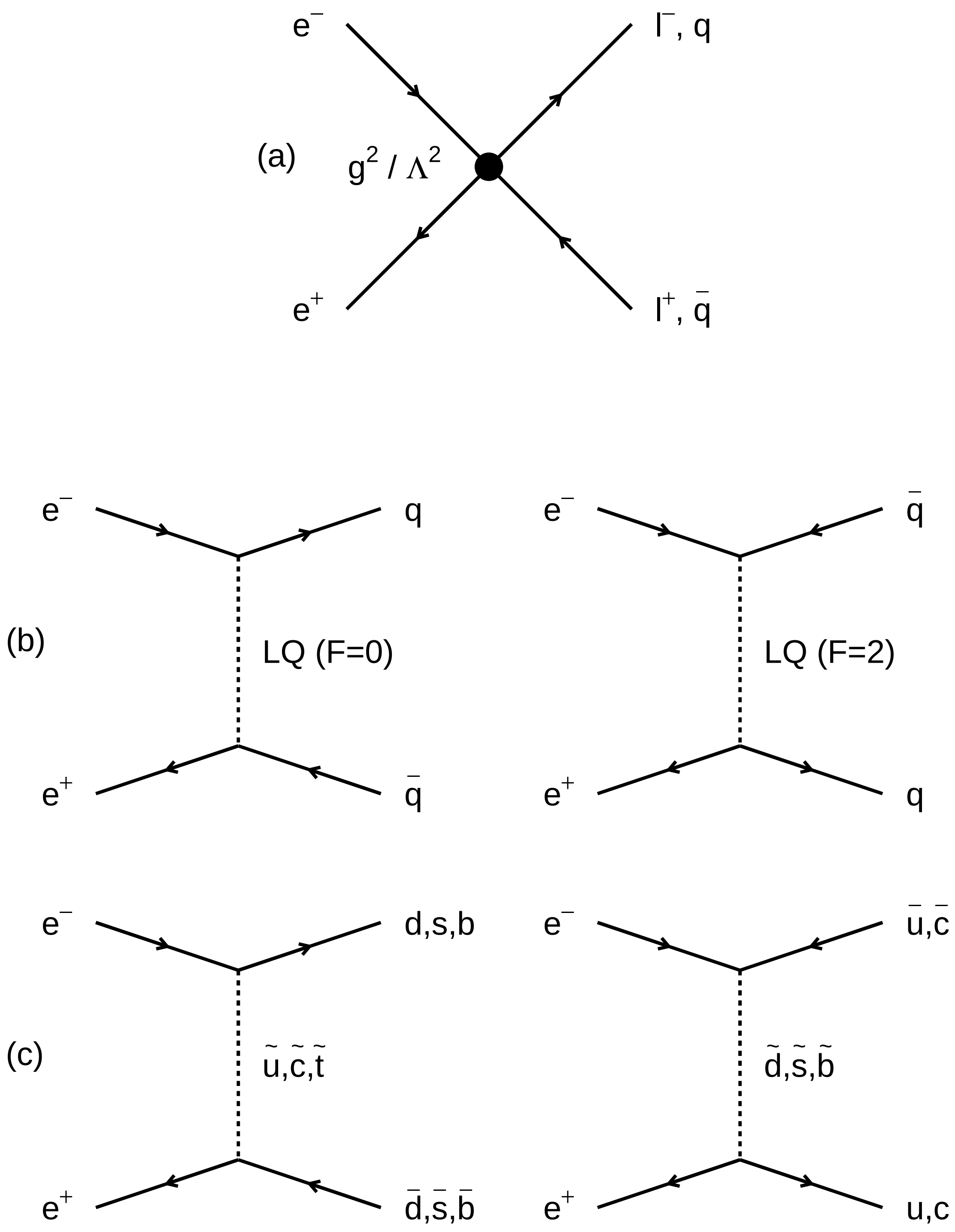

Figure 1: a) Feynman diagram describing the contact interactions; (b) Feynman diagrams describing the t–channel exchange, left, and u–channel exchange, right, of leptoquarks with fermion number $F = L + 3B$; (c) Feynman diagrams describing the t–channel exchange, left, and u–channel exchange, right, of scalar quarks.

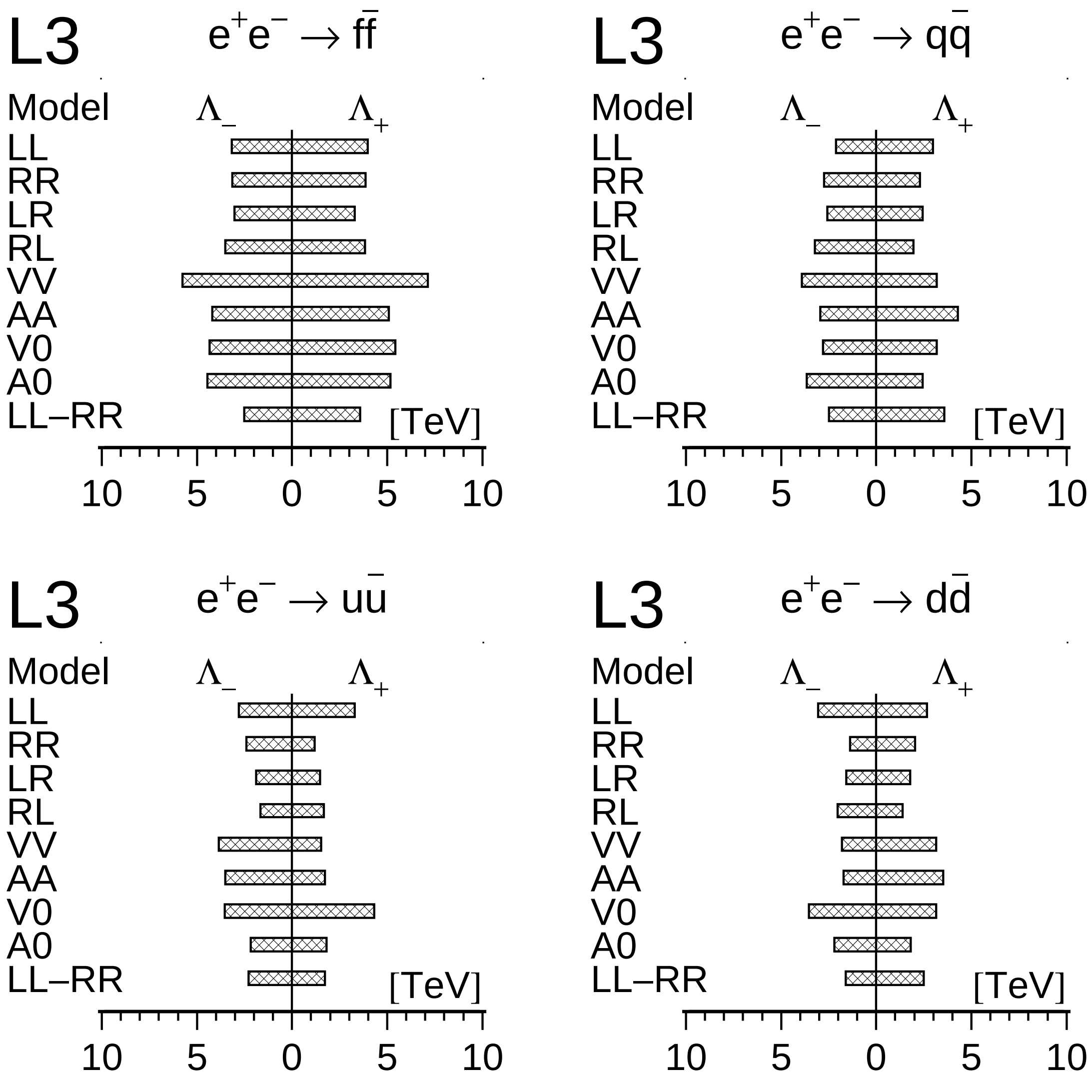

Figure 2: One–sided 95% confidence level lower limits on the scales Λ_+ and Λ_- for contact interactions in hadronic channels and in all channels combined. The limits correspond to the values given in Table 2.

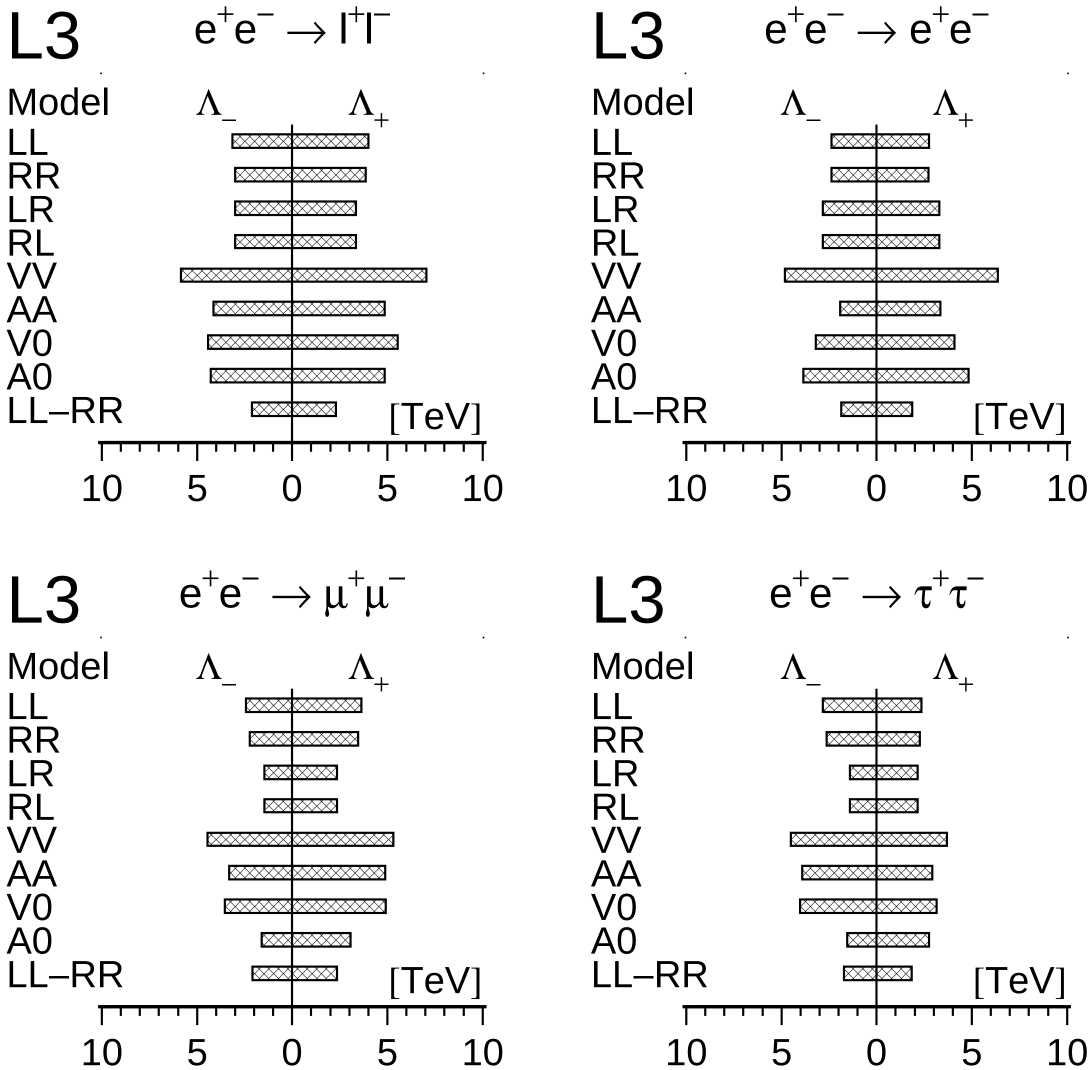

Figure 3: One–sided 95% confidence level lower limits on the scale Λ_+ and Λ_- for contact interactions in leptonic channels. The limits correspond to the values given in Table 3.

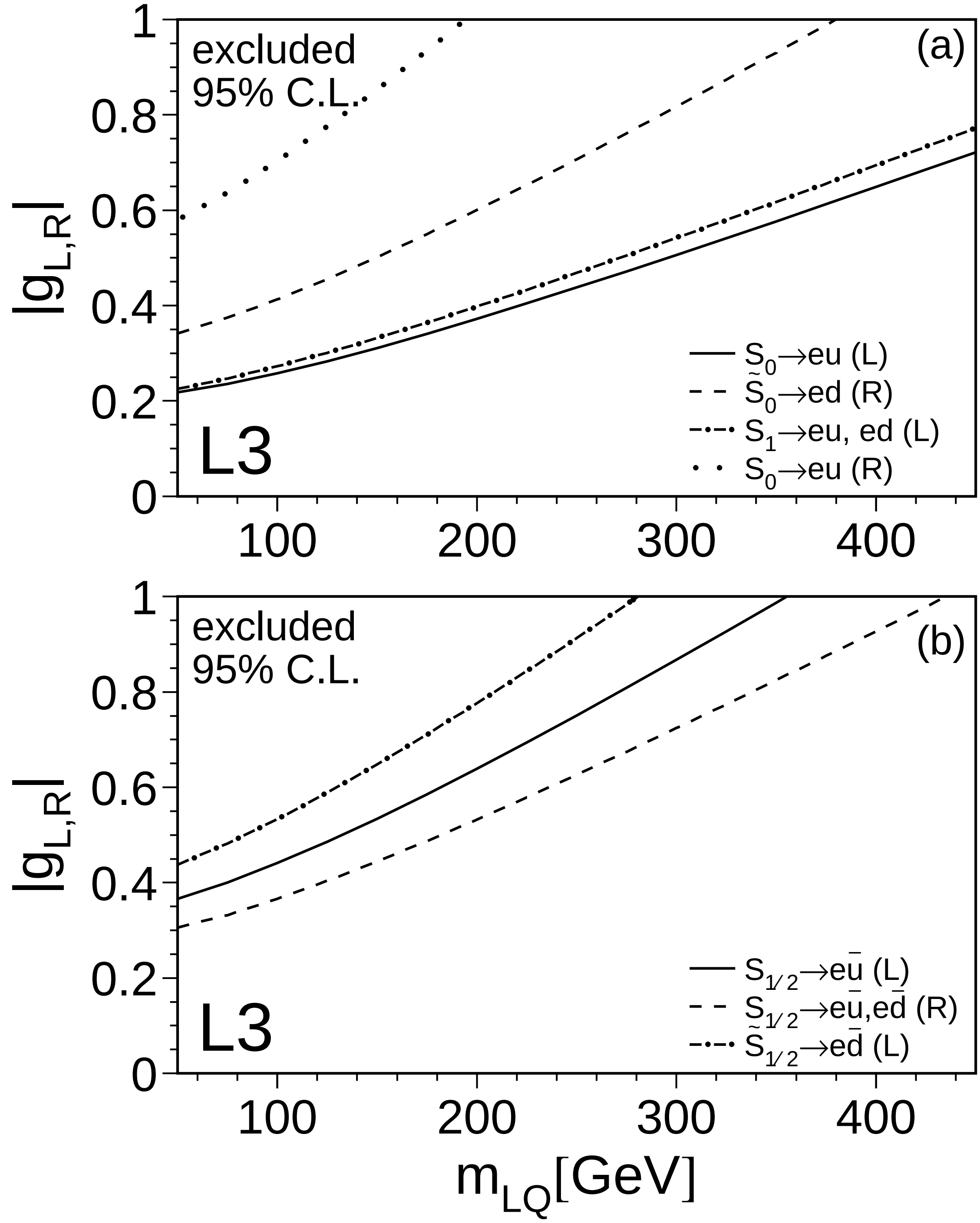

Figure 4: The 95% confidence level upper limits on $|g_{\mathrm{L,R}}|$ as a function of m_{LQ} for various scalar leptoquarks derived from hadronic final state cross sections. Limits are shown for fermion number F=2 (a) and for F=0 (b). Bounds on $|\lambda'_{1jk}|$ for the exchange of scalar down–type quarks in the u–channel and scalar up–type quarks in the t–channel agree with limits on $|g_{\mathrm{L}}|$ for the S_0 and $\tilde{S}_{1/2}$ leptoquark exchange, respectively.

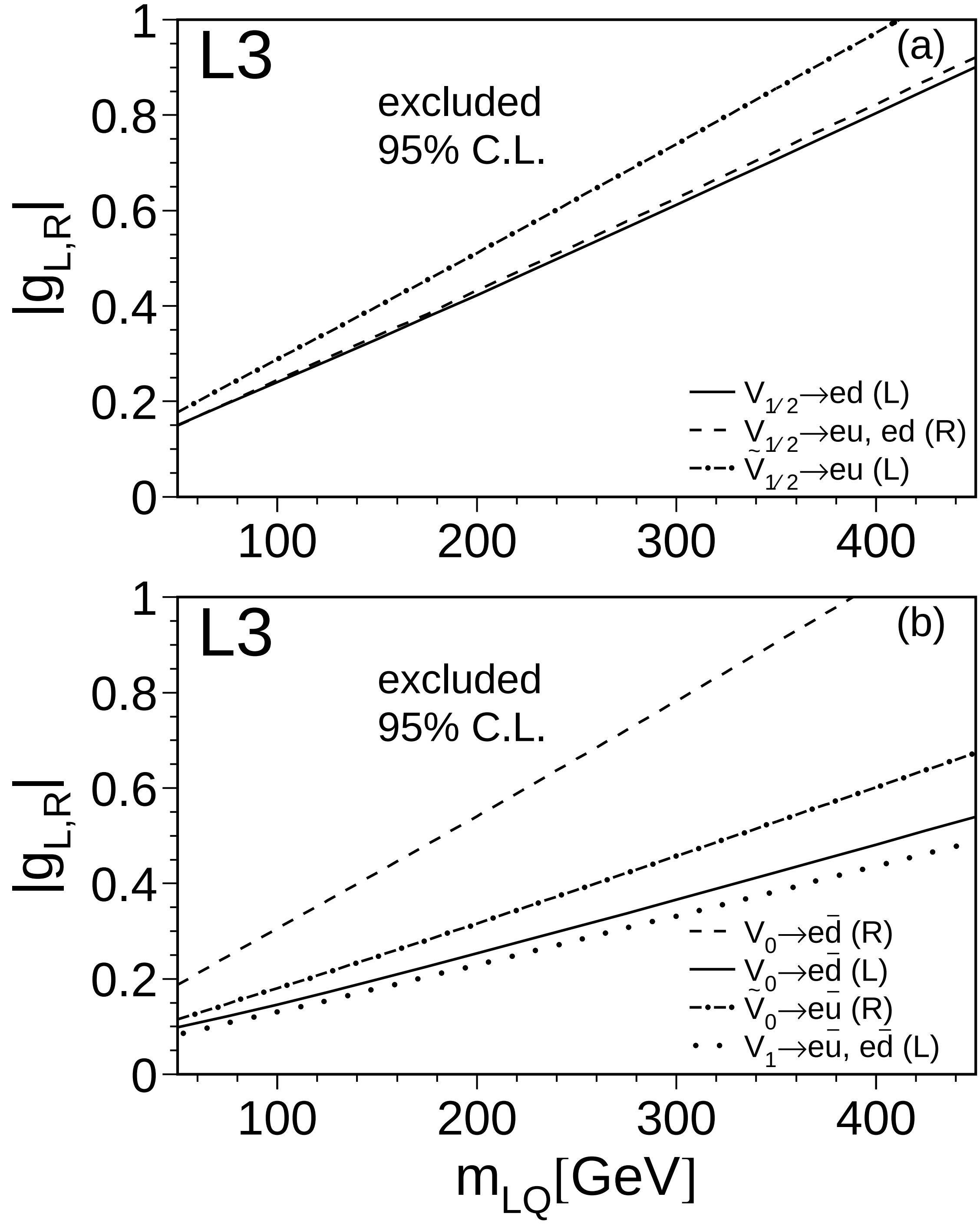

Figure 5: The 95% confidence level upper limits on $|g_{\mathrm{L,R}}|$ as a function of m_{LQ} for various vector leptoquarks derived from hadronic cross sections. Limits are shown for fermion number F=2 (a) and for F=0 (b).